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A STUDY IN FLOW CONTROL AND SCREENING METHODS FOR AIRCRAFT LASER TURRETS

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Final Report

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Air Force Systems Command
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application to separation control on aircraft turrets. A flow-control concept screening methodology is developed and applied to conceptual designs. The effectiveness of wind and water tunnel testing for screening flow-control concepts has been evaluated. Flow parameters have been bracketed and the simulation quality of the mechanisms of flow control established for each facility. Water channels are recommended for screening tests for many of the conceptual designs.

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I. INTRODUCTION

Technical issues regarding the aerodynamics and optics of aircraft turrets are of critical importance to the Air Force Weapons Laboratory (AFWL). Of specific interest are the optical properties of the flow over aircraft turrets, particularly in the separated flow aft of the turret. Flow separation from the outermost part of the turret produces an unsteady and turbulent shear layer in the turret wake. Turbulence generated by the flow separation imparts significant distortion on laser beams which propagate through regions of such intense fluctuations.

Control of flow separation from the outermost part of the turret, and the resultant development of the turret wake, will result in improved energy propagation particularly for aft targets. In addition, the overall drag and flow instability resulting from the turret can be reduced by the same methods which improve the optical characteristics of the flow. Development of effective flow control techniques can, therefore, be very beneficial to the AFWL's High Energy Laser (HEL) program.

This report describes the results of a modest survey of high-lift, airfoil flow-control technology, a flow control, screening methodology and the application of the methodology to conceptual flow-control designs.

1. AIRCRAFT TURRET DEVELOPMENT

A number of turrets have undergone extensive experimental evaluation in wind tunnels and on airborne laboratories. Early attention was directed at aerodynamic properties of the turret to insure its

compatibility with the aircraft. More recently, the aero-optics of aircraft turrets have been readdressed as an important issue for shorter wavelength lasers and for projection aftward through the turret wake. Wake turbulence has been demonstrated as a severe problem for short-wavelength lasers and aftward projection through the use of holographic interferometry by Trolinger (Ref. 1), and through the use of hot-wire anemometry by Rose (Ref. 2). Flight tests have shown that regions exist where flow-induced turret vibration causes unacceptably high beam jitter (Ref. 3). These results raise serious questions for the HEL program with regard to the use of laser weapon systems on airborne platforms.

Historically, turret aerodynamic investigations have been pointed at two distinct objectives. Initially basic aerodynamics tests were performed in which forces, moments, and general flow steadiness were measured. Windward and leeward fairings have been installed to smooth the flow around the turret and have been shown to reduce turret drag (Ref. 4). In the lower Mach number range ($M > 0.55$), windward, and particularly leeward, fairings reduced acoustic cavity oscillation. Porous fences and air injection have reduced acoustic cavity resonance by modifying the structure of the shear layer over the cavity.

The interest in the optical properties of the complicated turret flows resulted in the Aero/Optics I tests at NASA Ames in 1975. These were fundamental propagation tests in which the optical characteristics of turbulent boundary and shear layers were examined. During these tests, holography was employed by Trolinger (Ref. 5) to evaluate effects of fences, screens, and cavity blowing. Ames III testing of scale-model

turrets was the first wind tunnel turret test in which quantitative data on beam propagation were obtained. A significant result of the Ames III tests was the identification, through holography (Ref. 6), of the beam-distortion problem in the separated flow aft of the turret. In the Aero/Optics IV tests in 1978, small-scale turrets and generic fairings were tested with hot-wire anemometry and holography. During these tests, a new type of high-speed movie interferometer (Ref. 1) allowed, for the first time, a look at the dynamics of the turbulence. Quantitative flow-field data (Ref. 2) of the optical properties along several beam paths were produced which substantiated the aft-looking turbulence problem. The effect of wake turbulence was easily observed in later tests using holography (Fig. 1). Large-scale propagation tests are planned in which propagation information will be obtained from holography and hot-wire anemometry measurements.

2. MAIN OBJECTIVES OF TURRET FLOW CONTROL

The flow-control device should improve the optical quality of turret flow, particularly for aft-loading turret angles where separated flow is a severe problem. The optical quality of the turret flow is determined simply by the magnitude and scale of the density fluctuation and the total pathlength of the turbulence along the beam. To improve optical quality in the most straightforward method would be simply to reduce the thickness of the turbulent region. More exotic methods have been proposed by Jumper* in which the magnitude and scale of the turbulence are structured or reduced.

*Jumper, E., "Aero-Optics Overview," presented at Control of Turbulent, Separated Airflow about Aircraft Turrets Workshop, Air Force Weapons Laboratory, Kirtland Air Force Base, NM, March 1980.

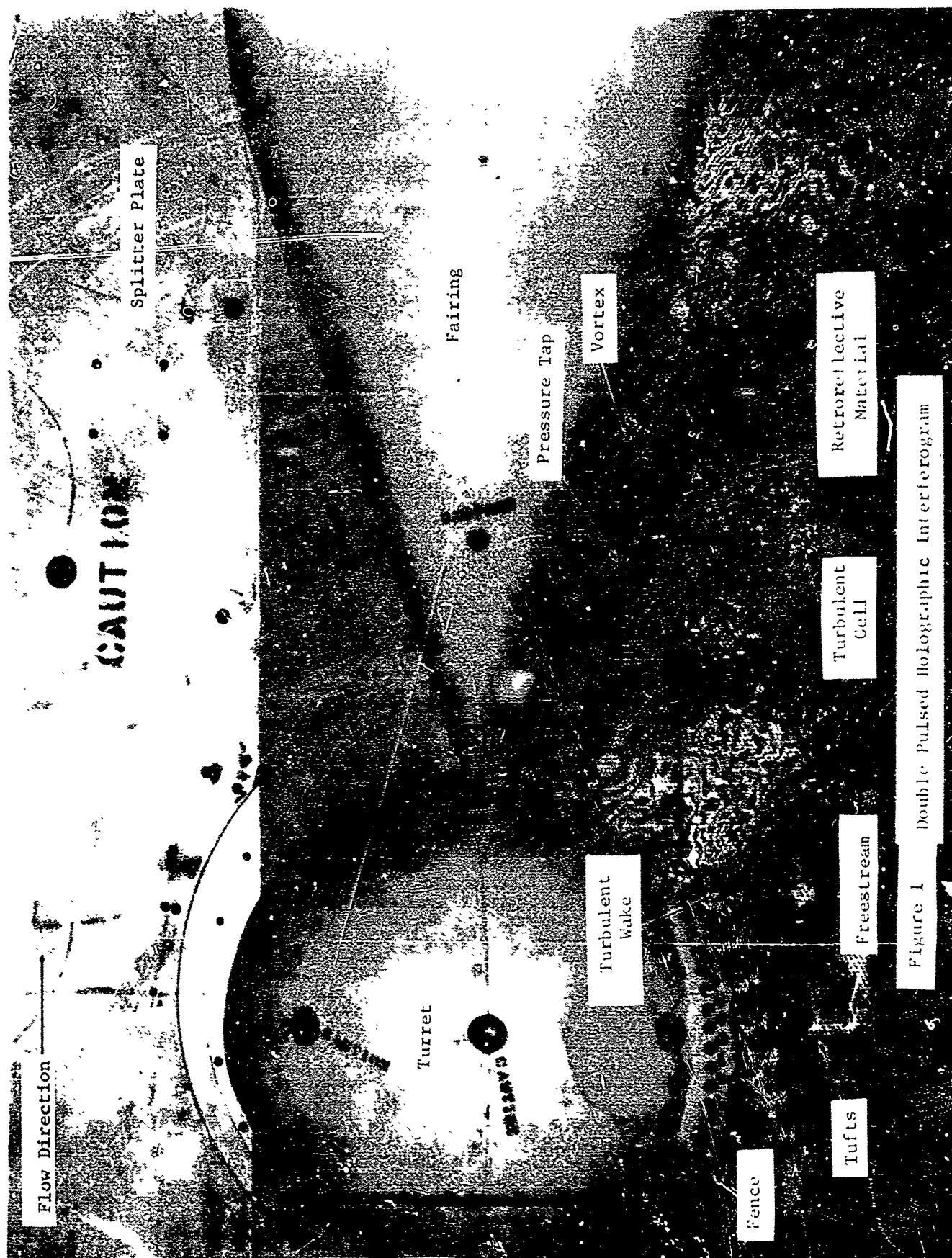


Figure 1 Double Pulsed Holographic Interferogram

The physical configuration of control techniques must be compatible with HEL mission requirements which, currently, are fairly broad.

Many of the proposed techniques require rather elaborate plumbing and mechanics to provide required suction or blowing. Initial attempts at active flow control should, therefore, be limited to off-turret designs where blowing and suction devices are more easily accommodated.

3. RELATED FLOW CONTROL TECHNOLOGY

The objective of turret flow control is the delay of separation beyond the turret port, especially when directed at aft targets. It is significant that the separation location on cylinder and spheres is known to be very sensitive to the base pressure. In fact, complete pressure recovery at the rear stagnation point has been demonstrated by Thwaites (Ref. 7) in incompressible flow when area suction was applied to the rear half of a cylinder. Large flow angles have been achieved near the trailing edge of airfoils using flow-control methods. Attached flow can be maintained in a number of ways: (1) by removing low momentum air at the surface through suction ports, or (2) by reenergizing the boundary layer with high momentum air blown along the surface.

One other common form of boundary layer control on bluff bodies is the promotion of early transition to turbulent boundary layer flow. The higher momentum turbulent layer separates farther along the body. This technique is normally accomplished with surface roughness elements, and is limited to flows in which the separation is originally laminar. For the Reynolds number range of aircraft turret operation ($Re/m \approx 10^7$), the boundary layer is typically highly turbulent and, therefore, the addition of roughness would not be effective for separation control.

The numerical prediction of the separation of turbulent boundary layers in regions of adverse pressure gradients at transonic speeds is a topic of current research. At transonic speeds, the adverse pressure gradient can be caused by shock wave interaction or by body curvature or, more typically, both. Current work by Horstman (Ref. 8) and by Viegas (Ref. 9) describes numerous turbulence models available for computer flow analysis. Some aspects of flow separation are predicted fairly well; namely, the location of separation and the pressure rise at separation. However, the flow beyond separation is poorly modeled, especially turbulence relaxation phenomena, after interaction with the shock.

Two generic flow-control concepts were identified by deJonckheere* in the Turret Flow Control workshop consisting of on- and off-turret designs. Most concepts were derived from existing high-lift airfoil technology of which some examples are described here with their proposed modifications for use on aircraft turrets.

(1) Suction Techniques - The control of separation at high angles of attack on the upper surface of wings by suction has been proven to be an effective means for increasing section lift coefficients. Schlichting and Pechau (Ref. 10) have shown suction to be most effective when placed in the region of rapid pressure rise downstream of the maximum velocity point. Higher suction velocities in that area were demonstrated to be more effective than uniformly distributed suction over the

*deJonckheere, R., "Control of Turbulent, Separated Airflow about Aircraft Turrets" Workshop, Air Force Weapons Laboratory, Kirtland AFB, NM, March 1980.

entire wing. Suction velocities slightly less than 1 percent of free-stream, when application to the front 20 percent chord, were required to prevent separation.

The use of suction for boundary-layer control on bluff bodies was used on the Thwaites Flap (Fig. 2) as a means for producing lift independent of the flow incidence. This concept involves a small flap attached to the cylinder base which fixes the rear stagnation point, provided sufficient boundary layer control is applied to the cylinder to maintain a completely attached boundary. Figure 3 depicts the pressure distribution about the cylinder for the case where the boundary layer was controlled by suction, and the rear flap angle was varied to adjust the lift. With a flap length of $1/5$ the cylinder radius, a lift coefficient of 9 was attained for a flap angle of 60 deg. The suction parameter, $C_Q(R)^{1/2}$, for attached flow varied between 20 and 33 for flap as a ratio of suction to free-stream velocity, and for Reynolds numbers of interest to aircraft turrets (say, 10^6 to 10^8), the corresponding velocity ratios would vary from 2 to 0.2 percent, respectively.

At transonic flow speeds, compressibility effects and shocks will occur that may alter the flow. The flow at the outer part of the turret has a supersonic flow region at freestream Mach numbers greater than 0.73 (Fig. 4). Under such flow conditions, the base pressure recovery will involve compression and shock waves.

The application of base suction to bluff bodies at transonic speeds has received little attention in the literature because most bodies that travel at transonic speeds are fairly slender (airfoils, missiles, and projectiles). However, considering work of Thwaites

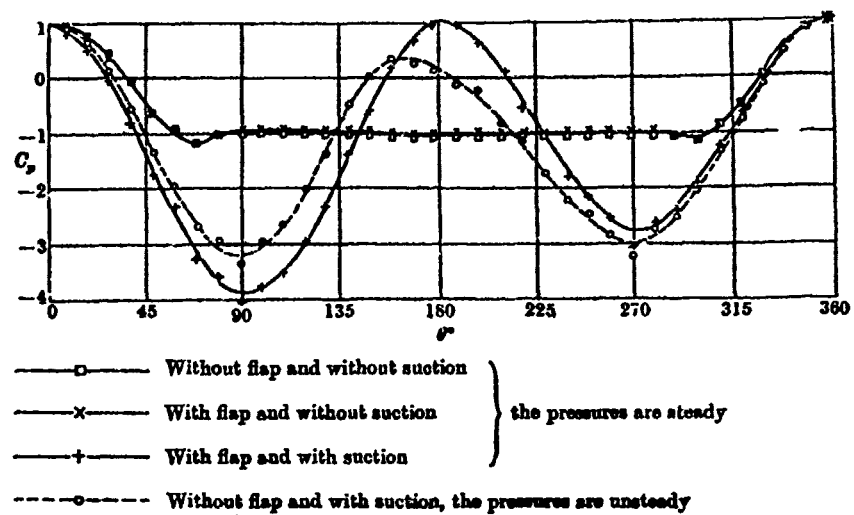


Figure 2. Pressure Distributions on a Porous Cylinder with and without a Thwaites Flap (Ref. 7)

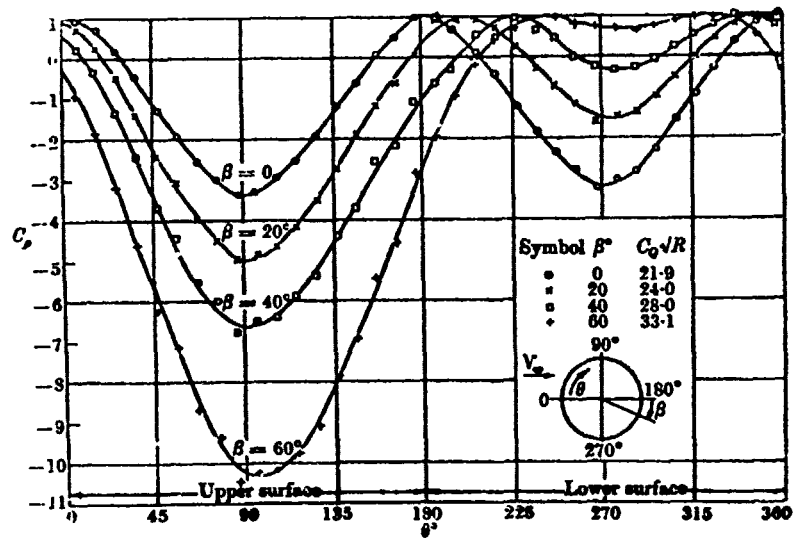


Figure 3. Pressure Distributions on a Porous Cylinder with a Thwaites Flap (Ref. 7)

FLAGGED, RN=3.8*10¹⁵/M
 UNFLAGGED, RN=4.9*10¹⁵/M

SYMBOL	MACH
○	1.49
□	0.95
◇	0.84
▽	0.73
△	0.62

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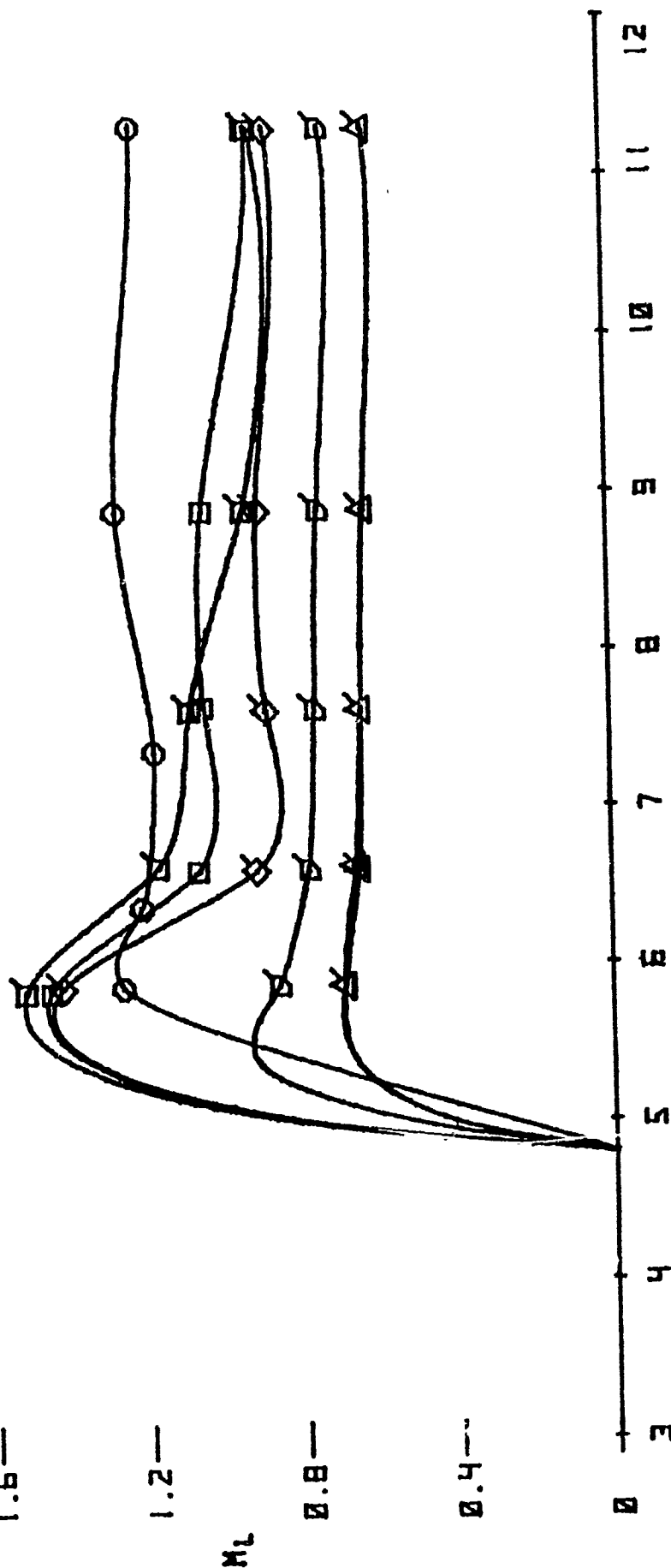
1.6 —

1.2 —

0.8 —

0.4 —

0 —



REP, CM

Figure 4. Local Mach Numbers along the Line of Sight from the Turret Cavity, $\theta = 90$ deg (Ref. 11)

(Ref. 7) on subsonic flows, it is expected that considerable pressure recovery will occur even for moderate amounts of suction. Base pressure recovery will produce considerable reductions in drag. However, Thwaites found that flow unsteadiness was not reduced until the rear stagnation point was fixed with a small flap. Using base suction with a small base flap on the turret, it is possible that substantial reductions in wake size are possible. Some flow configurations are shown in Figure 5, indicating the significance of the attendant reduction in turbulence extent.

(2) Blowing Techniques - The use of blowing has been proven to be an effective control of separation on the upper surfaces of wings and flaps. Blowing is a particularly attractive separation control technique because air may be bled from the jet engine compressor to a choked blowing slot. The effectiveness of slot or tangential blowing depends on the jet introducing sufficient momentum to prevent the local boundary layer from stagnating or separation. The blowing parameter is the momentum coefficient C_μ , (Ref. 12).

$$C_\mu = \frac{\dot{M}_J U_J}{q_\infty A}$$

\dot{M}_J = jet mass flow

U_J = jet velocity

q_∞ = freestream dynamic pressure

A = reference area (usually wing area)

The application of blowing as a boundary layer control mechanism has been shown to be quite effective for high lift airfoils (Fig. 6). Two

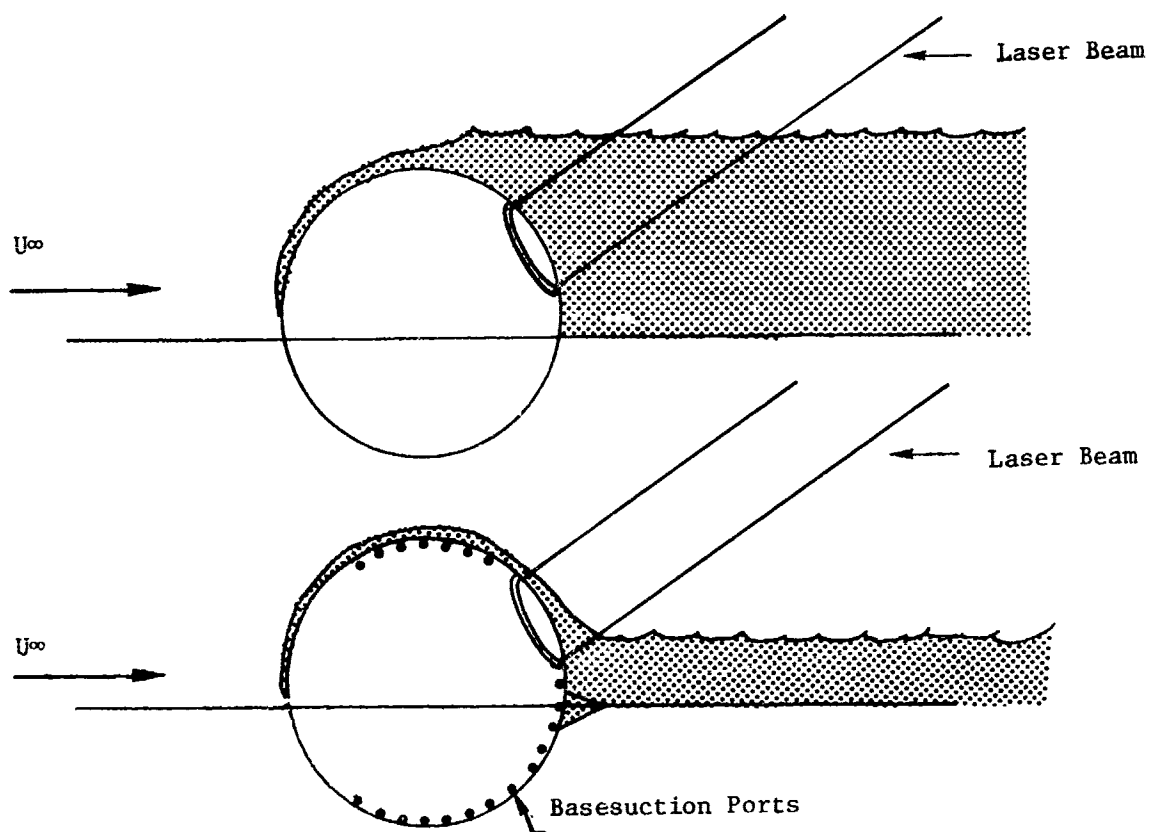


Figure 5. Reduction of Extent of Turbulent Wake through Base Suction.

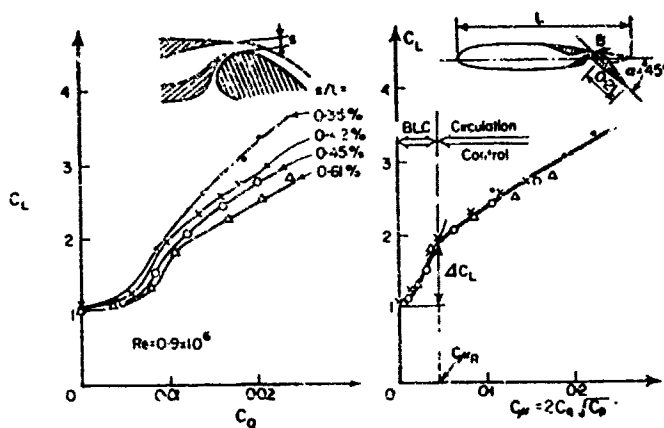
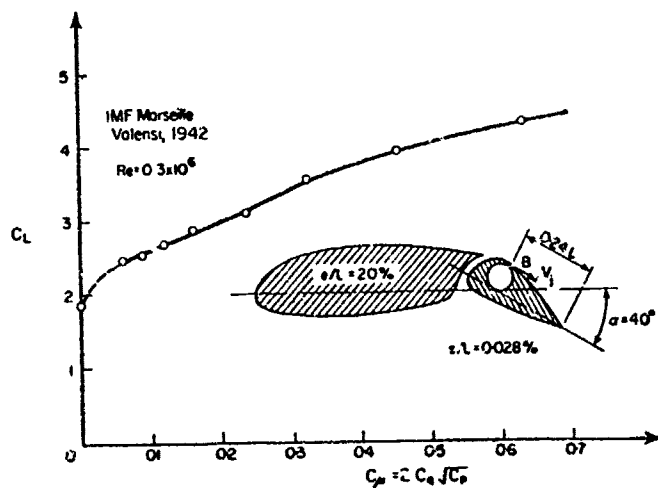


Figure 6. Boundary Layer and Circulation Control Using Slot Blowing. (Ref. 11)

regimes of control are identified: one denoted boundary layer control in which sufficient blowing is applied that boundary layer separation is avoided, and a second regime denoted circulation control in which increased blowing is applied, generating lift coefficients over and above the theoretical limit. Decreasing slot height, thereby increasing blowing velocity, is shown to have a beneficial effect for equal mass flows, illustrating that the momentum coefficient is the dominant parameter.

Compressibility effects complicate the use of blowing as a boundary-layer control technique because of the appearance of shock waves. The additional stagnation which occurs as the boundary layer passes through the shock wave can be sufficient to separate the boundary layer. Blowing in the shock interaction region can be an effective control method for weak shock strengths (Fig. 1). For higher freestream Mach numbers, or higher shock strengths, control effectiveness is completely lost.

One of the primary applications of slot blowing is shown in Figure 8, where the attached flow over a highly deflected flap is achieved. Since the jet momentum is important, it is better to increase jet velocity and decrease slot area than the opposite. The slot-blowing technique could be configured to achieve the equivalent flow as produced by suction on the Thwaites flap. A configuration, as shown in Figure 9, is possible even though the inner turret plumbing and nozzle geometry appear quite complicated.

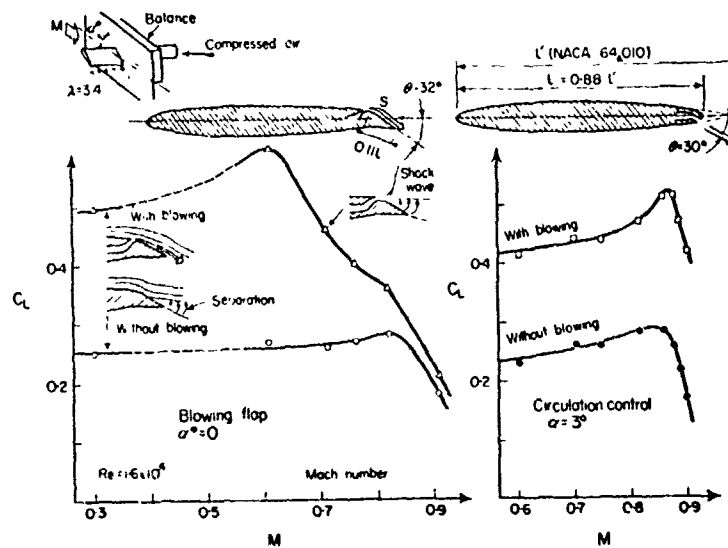


Figure 7. Compressibility Effects on Separation Control Using Slot Blowing (Ref. 11)

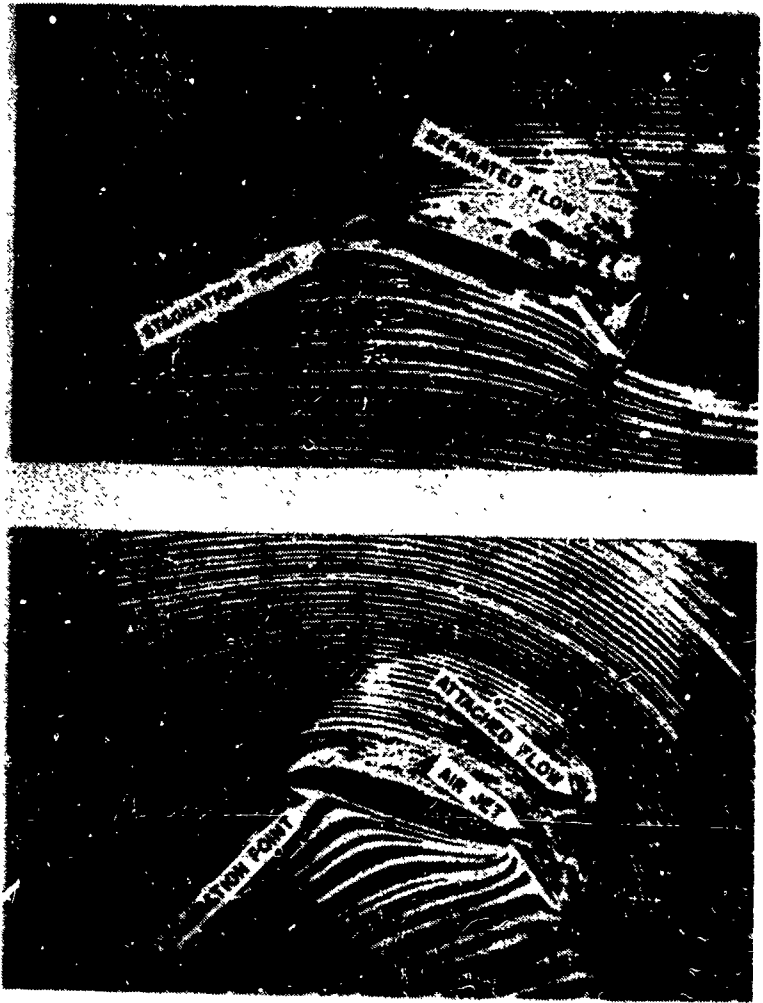


Figure 8. Uncontrolled and Controlled Flows about Flapped Airfoils at High Deflections (Airjet Boundary Layer Control) (Ref. 11).

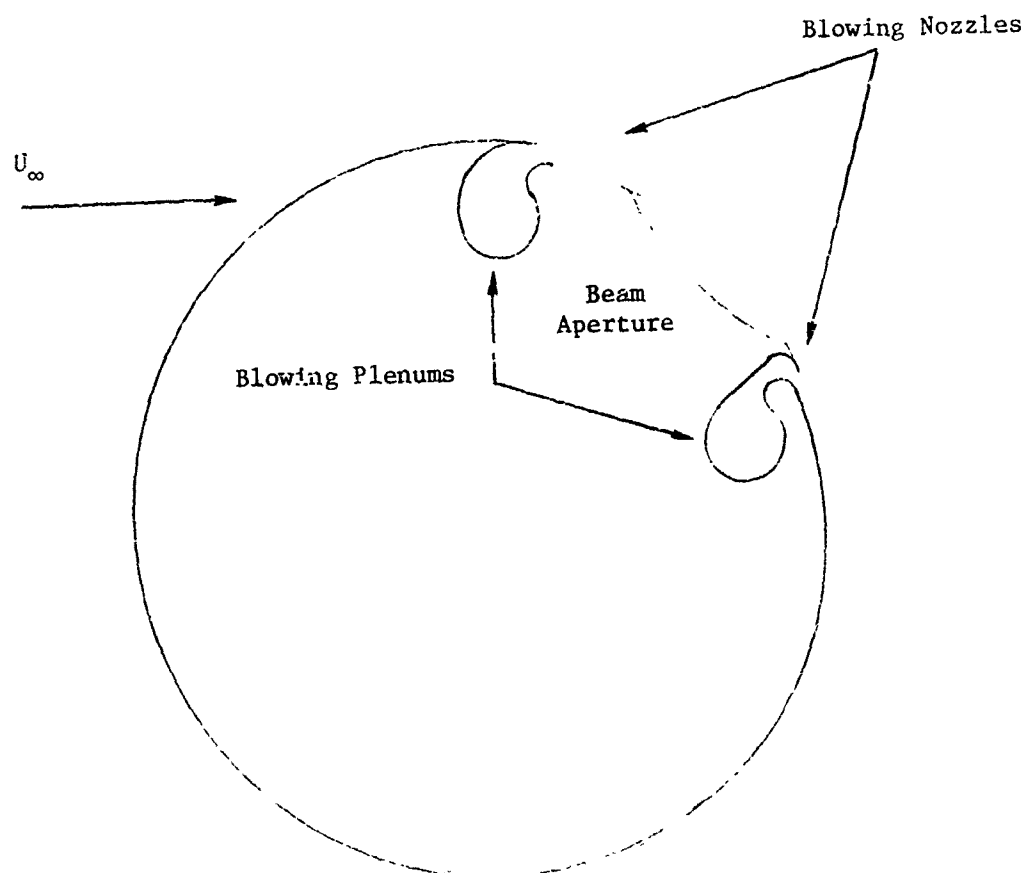


Figure 9. Conceptual Surface Blowing Flow Control.

(3) Hybrid Jet Pump Techniques - The ability to apply sufficient suction along the complete airfoil span is complicated by large-diameter, low-pressure ducts leading to the suction source. An alternate approach is a jet pump which is powered locally by high-pressure air (Fig. 10). The entrainment of the jet provides an effective suction in the ejector. This allows the beneficial use of both spanwise blowing and suction to create high section lift coefficients with reduced internal plumbing complexity.

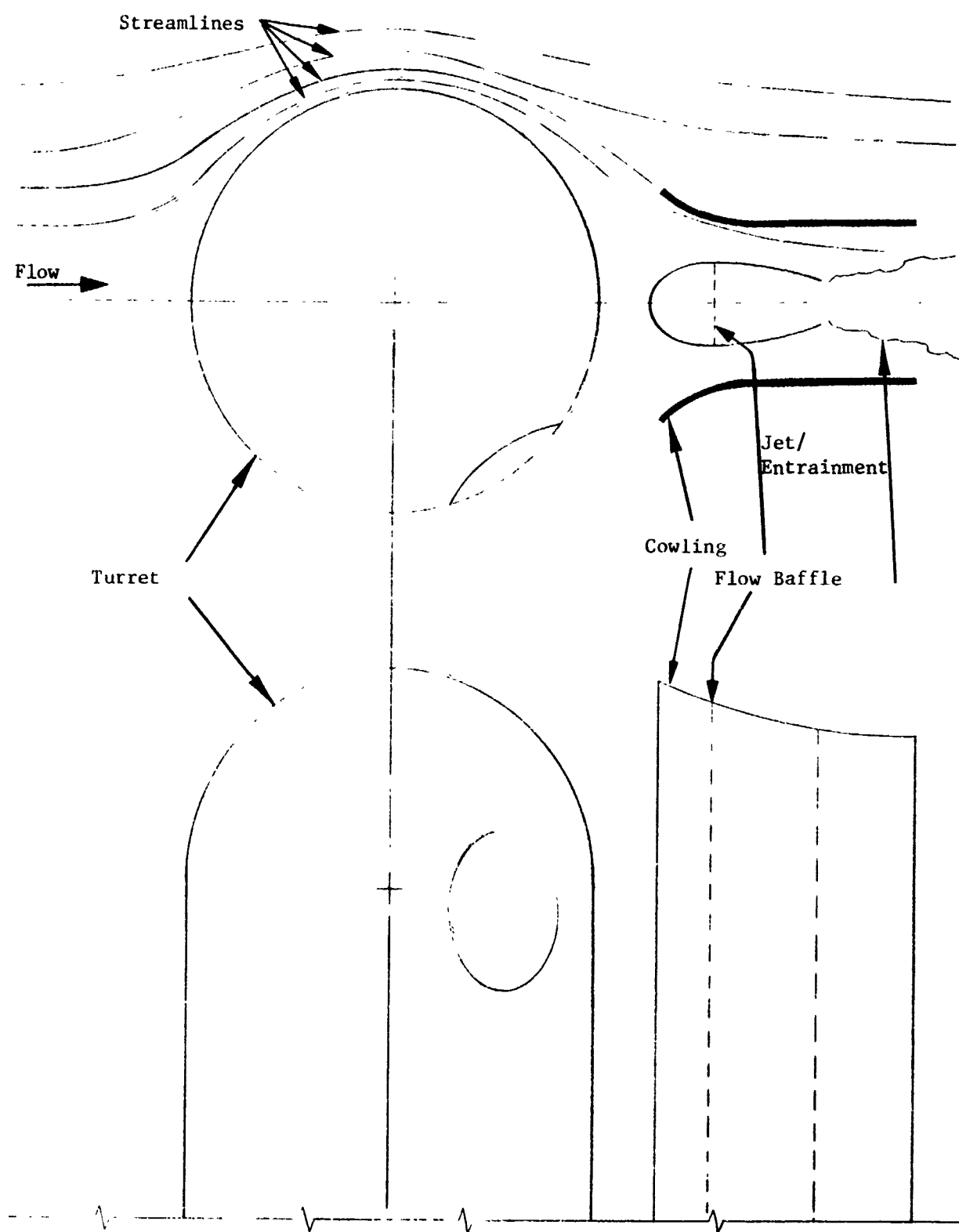


Figure 10. Combined Suction and Blowing with a Jet Pump.

II. CONTROLLED AND UNCONTROLLED TURRET AERODYNAMICS

Turret flow encompasses the most difficult fluid mechanics problems including three-dimensional turbulent boundary layer separation, shock wave boundary layer interaction in transonic flow with an unconstrained shock, and general flow unsteadiness. In addition, the flow is further complicated by a cavity flow in which Helmholtz or organ pipe-like, acoustic cavity resonance occurs. As a part of the Aero/Optics testing, the use of fence turbulence generators and a base fairing to alleviate the resonance, aerodynamic drag, and overall flow unsteadiness have been investigated. These tests have been very useful in identifying the character of the flow field and in defining the areas that require further investigation.

1. BASIC TURRET FLOW CHARACTERISTICS

Although the turret flow is essentially three-dimensional, the simplified transonic flow about a cylinder can be used as a starting point in attempting to better understand and estimate the effectiveness of the methods of flow control. Boundary layer separation on the cylinder is expected to be affected by both pressure gradient and shock wave interaction. As in transonic airfoil separation, as described by Bachalo^{*}, the shock may be of insufficient strength to separate the turbulent boundary layer but does serve to remove momentum from the

^{*}Bachalo, W. D. and Johnson, A. A., "An Investigation of Transonic Turbulent Boundary Layer Separation Generated on an Axisymmetric Flow Model, "AIAA-79-1479, Presented at AIAA 12th Fluid and Plasma Dynamics Conference, Williamsburg, Virginia, July 1979.

flow. With a stronger shock, the combination of the shock and the aft pressure gradient combine to produce separation at the foot of the shock.

The critical Mach number for the flow about a cylinder is approximately 0.42 (Ref. 13). At Mach numbers greater than this, a region of supersonic flow forms bounded by the sonic, $M = 1$, line and terminated by a shock, (Fig. 11). As the freestream Mach number increases, the strength of the shock increases proportionately and has a more severe effect on the boundary layer. Removal of momentum from the boundary layer manifests as an increased displacement thickness. This, in turn, appears as an increase in the cylinder diameter and moves the shock.

Reference 14 identified the importance of dividing the wake centerline downstream of the cylinder in reducing vortex shedding. A partition 4 or 5 diameters in length was sufficient to block communication between the two shear layers on either side of the wake, thus, the roll-up mechanism which stabilizes the periodically alternating vortex formation is prevented. The drag coefficient is also markedly affected by the partition, as evidenced by the increase in the base pressure from $C_p = -1.0$ without partition to a $C_p = -0.5$ with partition (Fig. 12a). Another significant point is the identification of a pressure valley about 1 diameter downstream where the vortex formation occurs in the absence of a partition. The flow dynamics in the region of vortex formation creates a low pressure which results in a suction on the cylinder base.

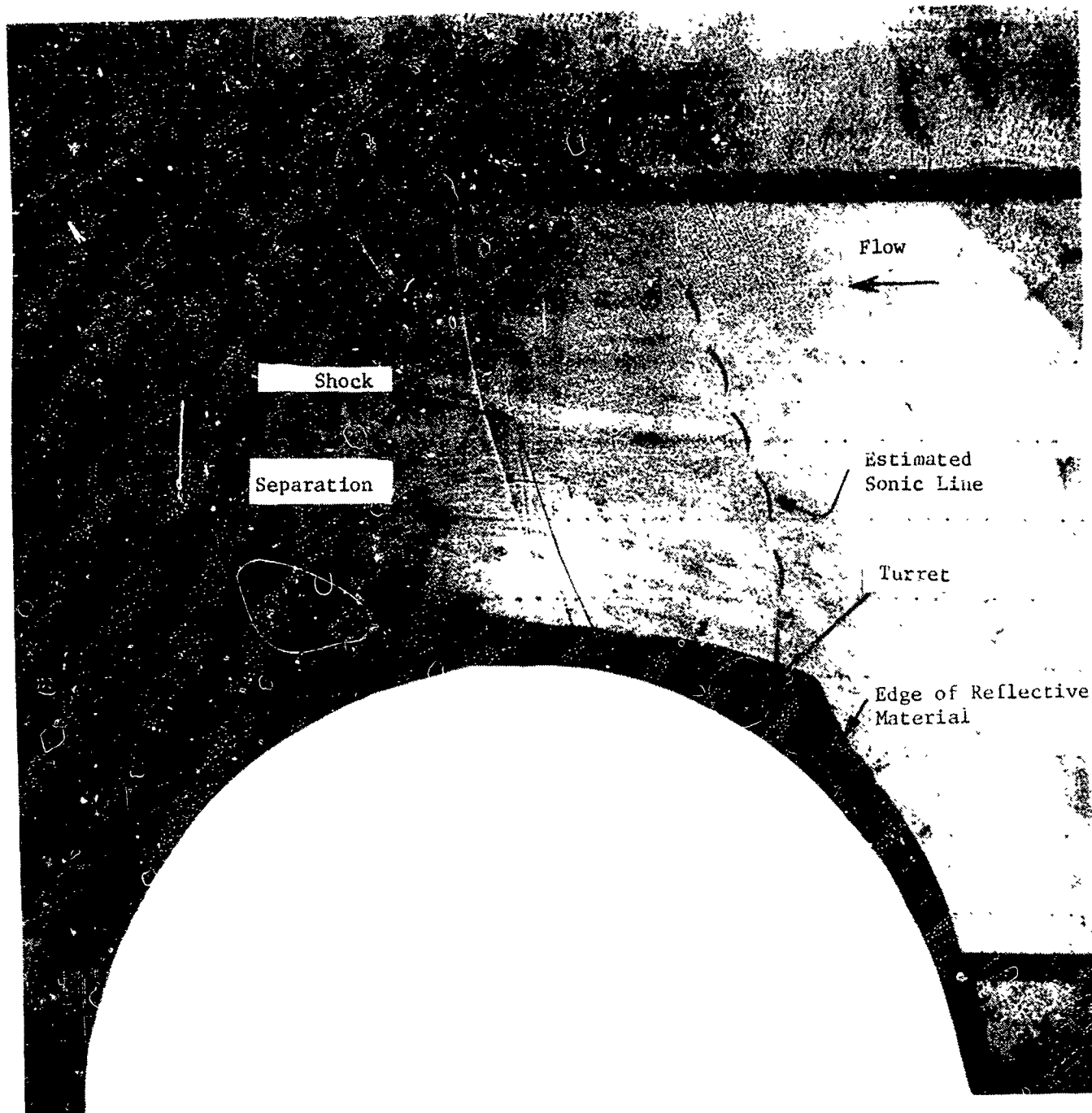


Figure 11. Shadowgram of Turret Flow (Plan View)
Ames I Testing in 14-ft Tunnel ($M_\infty = 0.9$)

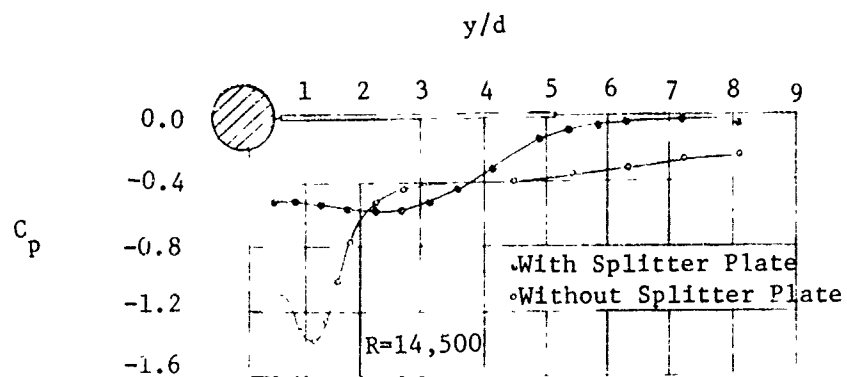


Figure 12a. Pressure on Wake C_L (Ref. 14)

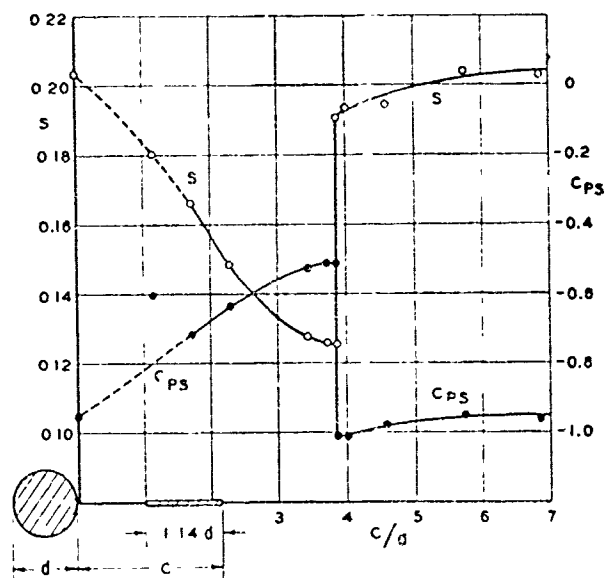


Figure 12b. Wake Interference (Ref. 14)

A similar effect was demonstrated with a shorter partition which was progressively moved downstream (Fig. 12b). As the partition was moved downstream, the base pressure increased to a maximum ($C_p = -0.5$) which was approximately equal to the value attained with the larger partition. When the partition was moved further downstream, vortex formation about the cylinder base was apparently reinstated and the base pressure returned to its nominal value, ($C_p = -1.0$).

These conclusions, generated by investigations into bluff body flows at subsonic speeds, are also reproduced at transonic speeds, as evidenced by the marked reductions in measured turret drag coefficients reported by McDermott (Ref. 4) and shown in Figure 13. The conclusion seems to hold over a large range of Reynolds numbers as the drag data are reported from 1/40th scale tests to full-scale flight tests, i.e., ($10^5 < RE_D < 10^7$).

Flow visualization of the turret flow with fairing in place, reported by Trolinger (Ref. 1), revealed some of the additional effects of compressibility. High-speed interferometer movies revealed an unsteady shock wave (Fig. 15) which was observed either on the turret or oscillating in the turret near wake. The lower-speed phenomena are also present as evidenced by the boundary layer separation and the vorticity roll up shown in Figure 14.

On the turret model, the combination of the unsteadiness and general turbulence behind the separation region produced high fluctuation levels as evidenced by the base pressure fluctuations of about 10 percent of the local pressure as measured by Raman (Ref. 15), and outer edge velocity fluctuations greater than 20 percent as measured by Rose (Ref. 2).

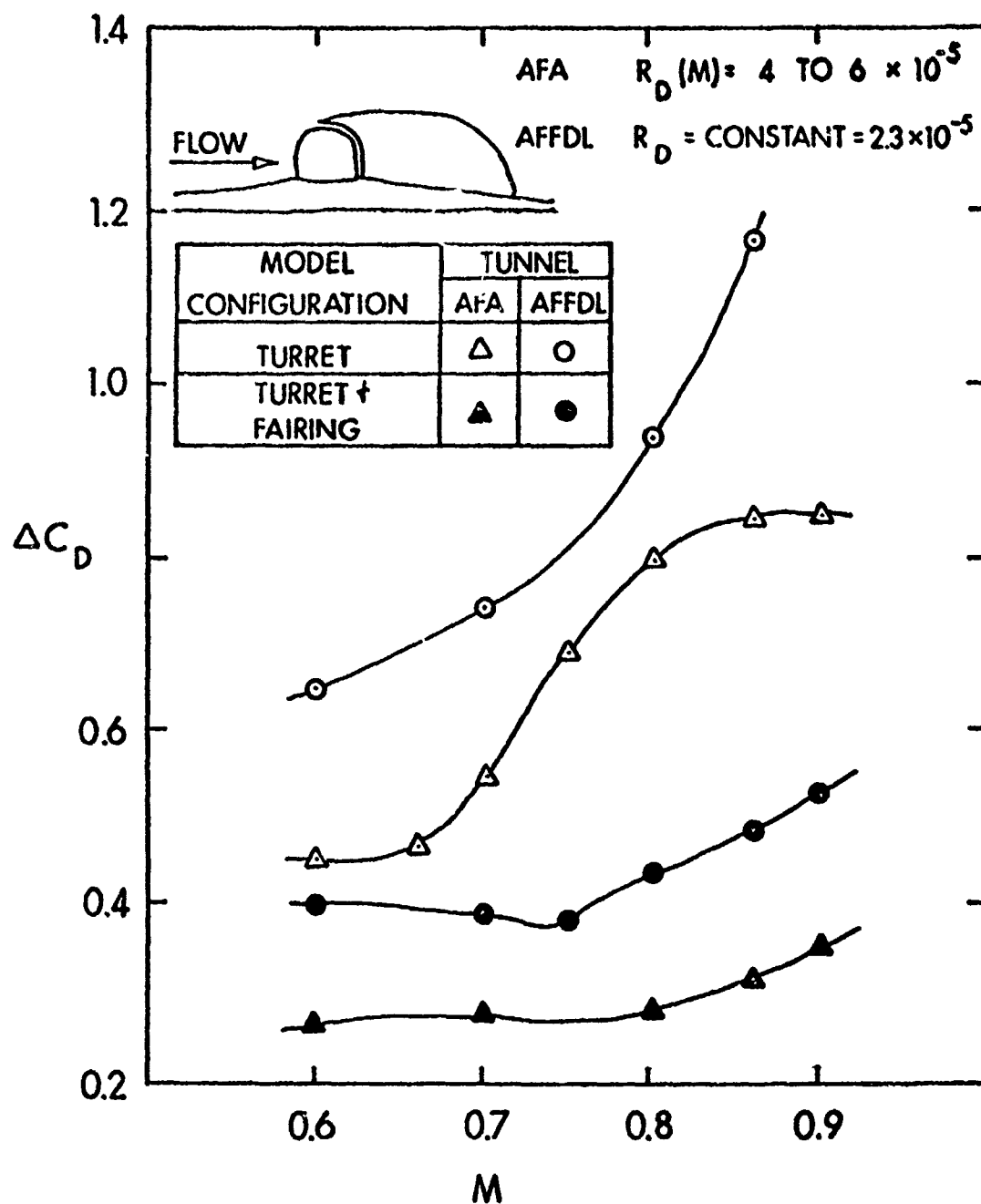


Figure 13. Turret Drag Coefficients with and without Base Fairing (Ref. 4)

EDDY MOTION IN WAKE

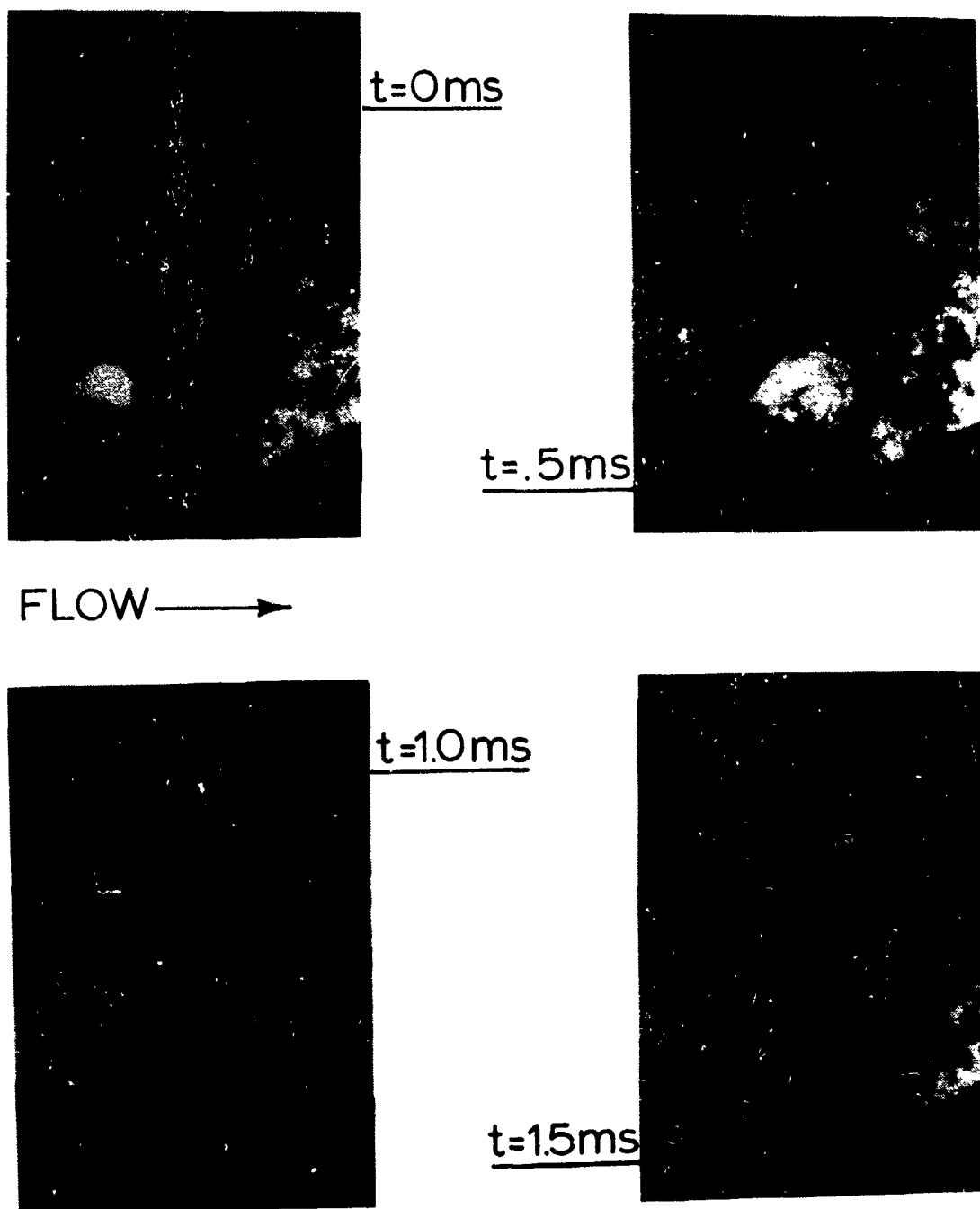


Figure 14. Eddy Motion in Wake Observed in High Speed Shadow Graph Movies

SHOCK MOTION IN EXTERNAL FLOW

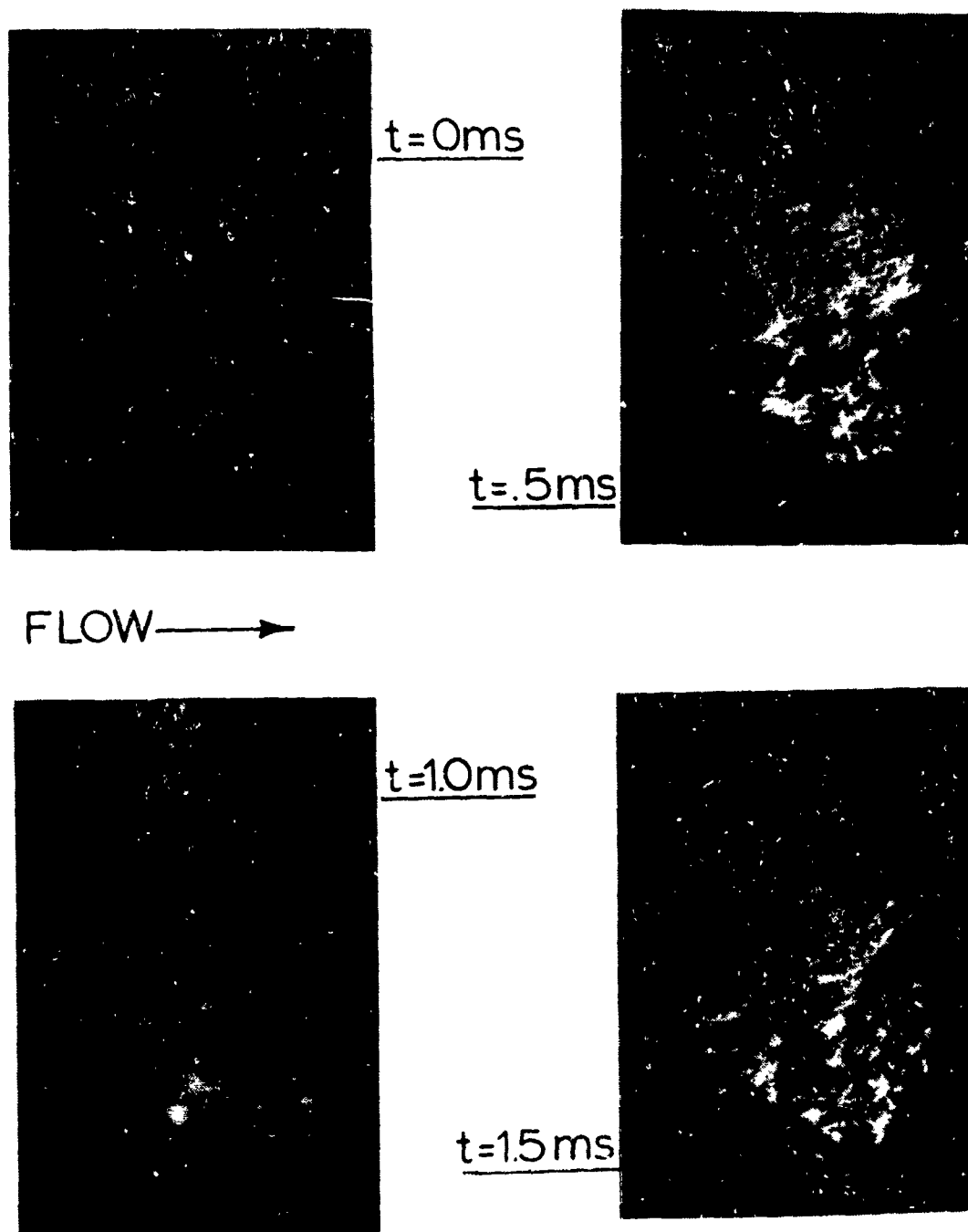


Figure 15. Shock Motion in External Flow from High Speed Shadowgram Movies

At separation, the vorticity production is so rapid that sheets of fluid are observed to roll up and form discrete vortices as the fluid detaches from the surface. These vortices entrain fluid from both sides of the cylinder as they move into the wake. Diagrams of the formation and dynamics of these vortex structures have been compiled by Cantwell (Ref. 16) for compressible flows.

2. OPEN PORT AND CAVITY EFFECTS

The open-port turret allows the passage of high energy laser beams from the aircraft without propagation through a material window. Large aperture material windows for high energy laser beams are apparently not suitable for aircraft applications. However, the open-beam port is by no means a perfect aperture and imposes many severe design constraints on the turret.

The aerodynamics of the open port is quite complicated; it is a strong function of port angle as well as freestream conditions. Two deleterious effects of the open port are noted here. The use of porous fences about the port circumference to reduce acoustic cavity resonance creates a strong turbulent shear layer across the aperture which scatters energy from the beam. The porous fence, however, has the positive effect of reducing the vibrational environment for internal turret optics. A suitably designed, porous fence must balance these positive and negative effects.

A second method of port flow control which has been the object of limited, but by no means insignificant, investigations is tangential or internal port blowing. The versatile control aspects of port blowing

makes the concept very attractive to overall aerodynamic control of the turret flow field.

(1) Cavity Pressure Fluctuations - Internal cavity pressure fluctuations have been widely investigated for the flat plate configuration, and the more complicated case, where the cavity is in a turret has also been studied.

Buell (Ref. 17) reports data for a rectangular cavity mounted in a flat plate aligned with the flow. The effectiveness of the porous fence, porous cavity wall, and cavity mass injection techniques is compared (Fig. 16). Mass injection was shown to further improve Model 15 (Table I).

The more complicated case of the turret cavity is reported by Thomas (Ref. 18), where the effect of porous fence height on cavity pressure fluctuation and turret torques was addressed. Mass injection from the turret lip, as well as from inside the cavity, was also investigated. Porous fences of modest height (height to turret diameters of 1/16) with 30% porosity were found to reduce internal pressure fluctuations by more than a factor of 2; however, this accomplishment was achieved only at the expense of doubling the unsteady turret torques.

Mass injection from within the turret cavity was shown to be most effective in reducing unsteady turret torques (Fig. 17). Tangential mass injection from a slit in the upstream edge of the cavity (Fig. 18) was just as effective with half the mass flow. The higher efficiency of tangential slot injection is due to the higher injection velocities as well as the geometric configuration.

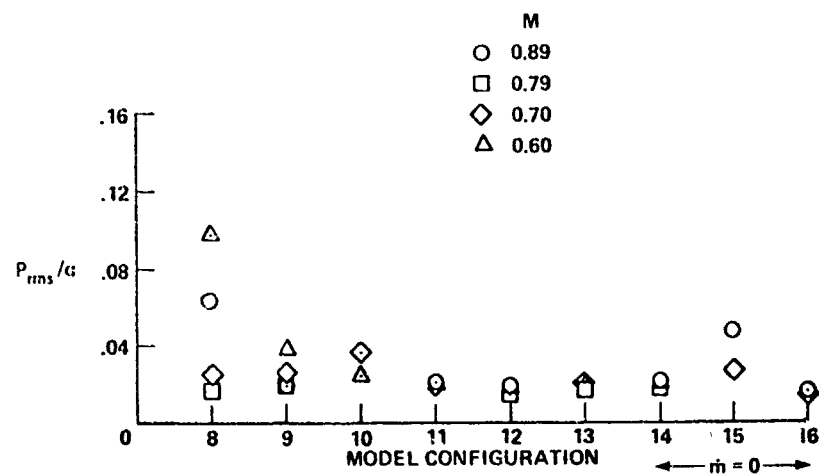


Figure 16. Fluctuating-Pressure Coefficients in the Cavity for Various Model Configurations (See Table 1 for Model Identification) (Ref. 17)

TABLE 1. MODEL CONFIGURATIONS (Ref. 17)

No.	Seed pins	Turbulence-generating pins	Return mirror	Fence height, cm	Fence porosity	Fence hole diameter, cm	Cavity	Upstream wall porosity	Upstream wall hole diameter, cm	Step height, cm	Probe measurement
1	X	X	X	—	—	—	—	—	—	—	X
2	X	—	X	5.1	0.49	0.37	—	—	—	—	X
3	X	—	X	—	—	—	—	—	—	—	—
4	X	—	—	—	—	—	—	—	—	—	—
5	X	—	—	5.1	0.49	0.37	—	—	—	—	—
6	X	X	—	—	—	—	—	—	—	—	—
7	X	—	X	5.1	0.53	0.95	—	—	—	—	—
8	X	—	X	—	—	—	X	0	—	—	X
9	X	—	X	2.3	0.38	0.24 slits	X	0	—	—	—
10	X	—	X	2.3	0.38	0.52	X	0	—	—	—
11	X	—	X	4.6	0.38	0.52	X	0	—	—	X
12	X	—	X	4.6	0.58	0.99	X	0	—	—	—
13	X	—	X	2.3	0.58	0.99	X	0	—	—	X
14	X	—	X	—	—	—	X	0.49	0.32	—	X
15	X	—	X	—	—	—	X	—	0.54 slot	—	—
16	X	—	X	2.3	0.58	0.99	X	0.49	0.32	0.64	—
18	—	—	X	—	—	—	—	—	—	—	—
19	—	—	X	—	—	—	—	—	—	—	—
20	—	X	X	—	—	—	—	—	—	—	—
21	—	X	X	—	—	—	—	—	—	0.64	—

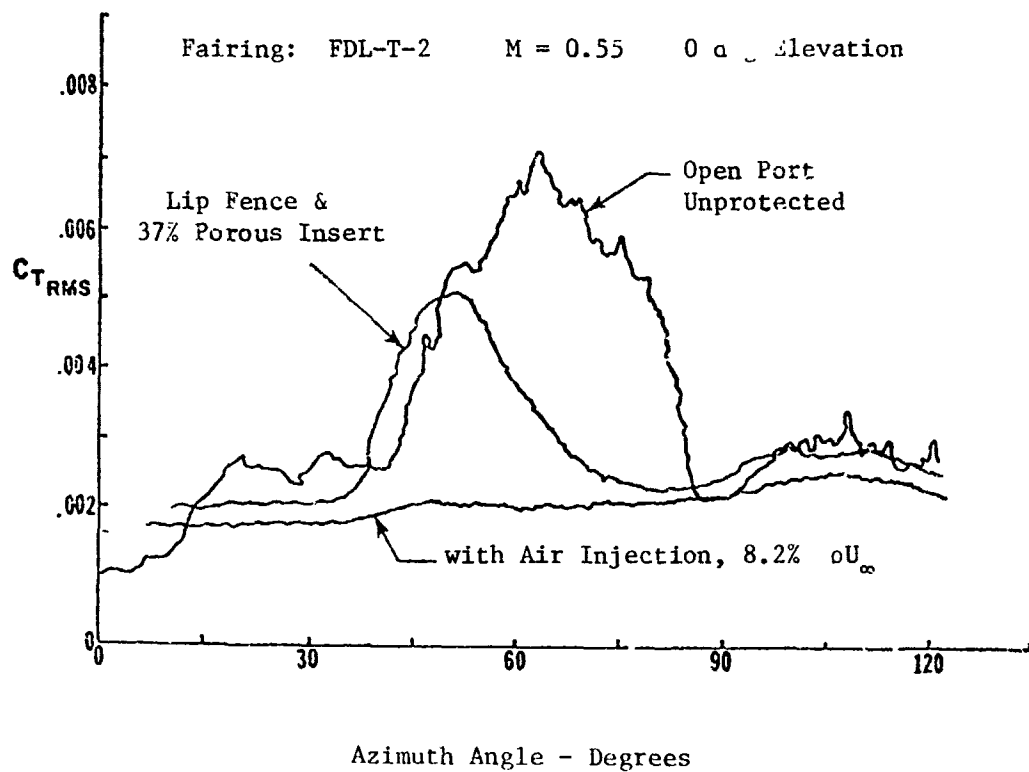


Figure 17. Unsteady Azimuth Torque Comparisons (Ref. 18)

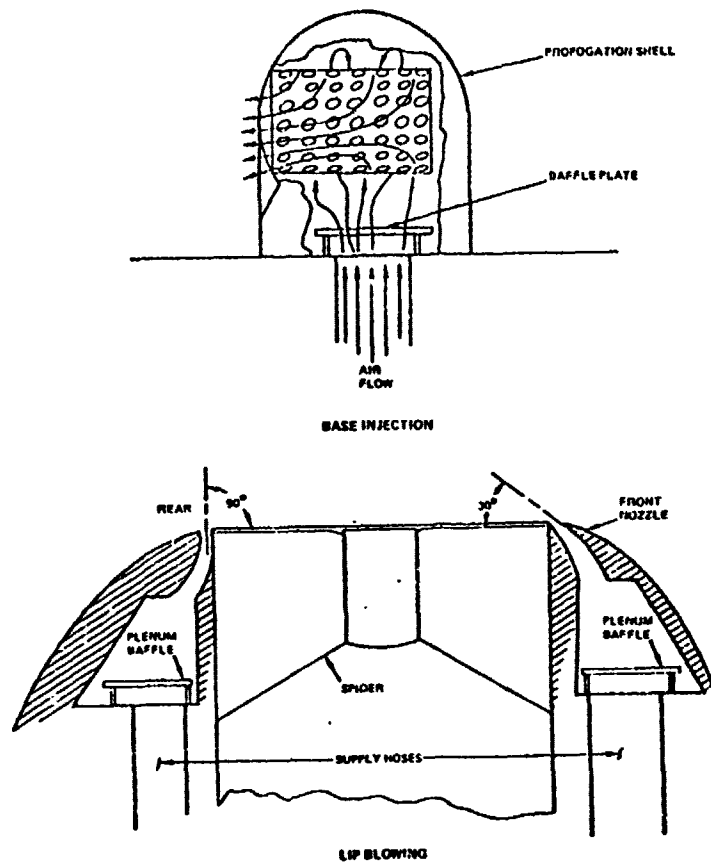


Figure 18. Techniques for Air Injection (Ref. 18)

(2) Turbulent Free Shear Layer - The beneficial effects of the porous fence have to be balanced against the deleterious effect the turbulent shear layer has on the beam quality. A shear layer develops across the port because the turret airflow must decelerate from the focal velocity at the upstream edge of the port to a considerably reduced velocity within the port cavity. The turbulence resulting from the shear causes velocity and density fluctuations, the latter of which scatters beam energy

Haslund* has described a simplified analytical model of the shear layer development across the port which quotes a fairly extensive amount of data in support of the assumed spreading angle and correlation length. An example beam distortion calculation for flight conditions of Mach 0.85 at an altitude of 35,000 ft. showed fairly large amounts of scattering (beam intensity was reduced 60%) particularly at 1.3 μm wavelength with a 2.0 m aperture diameter.

(3) Across Aperture Blowing - The use of tangential slot blowing at the upstream edge of the port may not only be useful for the control of internal turret pressure fluctuations but also for the control of the external flow field for aft-directed ports. Thomas (Ref. 18) has shown the beneficial effect of reducing internal pressure fluctuations but has not made any observations of the extended flow field. A conjectured flow field for a turret port angle of 120 deg. is shown in Figure 19, where the upstream edge of the port is very near the nominal separation point. Slot blowing at this station may require injection velocities

*Haslund, R. "Aero-Optic Shear Layer Modeling" presented at Control of Turbulent, Separated Airflow About Aircraft Turrets Workshop, Air Force Weapons Laboratory, Kirtland Air Force Base, NM, March 1980.

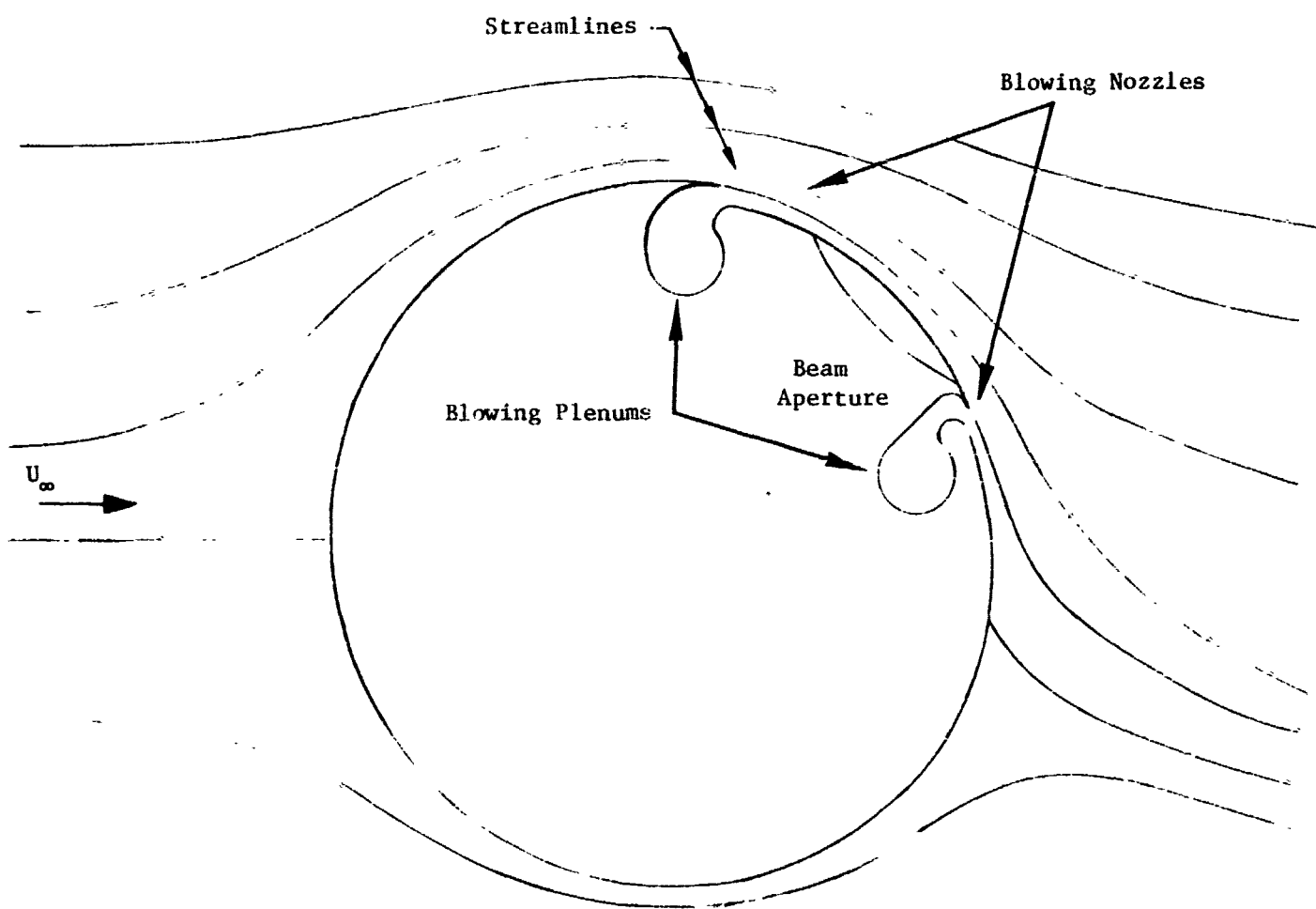


Figure 19. Conceptual Flow Field for Across Aperture Blowing

which are either sonic or supersonic since, locally, the edge Mach number is supersonic (Fig. 4). The primary beneficial effect is the reduction in turbulent pathlength caused by the control of separation; however, the beneficial effect in pathlength reduction must be balanced against the higher shear layer velocities across the turret aperture.

3. BASE-FAIRING CONCEPTS FOR ACTIVE FLOW CONTROL

The use of a turret base fairing is very beneficial to the basic turret aerodynamics; however, the flow-field effects apparently have little impact on the optical quality of the flow (Ref. 2). Aero-dynamically, the fairing has the effect of inhibiting periodic vortex shedding and eventual roll-up which apparently has the overall effect of increasing the base pressure (i.e., decreasing the drag coefficient).

The use of aerodynamic controls on the base-fairing seems quite logical with the success of passive fairings. In addition, the complexity of internal turret plumbing (the other most likely alternative) encourages one to seek external turret concepts and the base-fairing is a likely place to start. A number of active base-fairing concepts are described here including suction and blowing concepts, hybrid concepts using jet pumps, and trapped vortex concept with a cusped fairing and base suction.

(1) Base Suction - Base suction can be applied through the front of existing fairing or fairing modified specifically for suction. The modified fairing should be at least 1 turret diameter in length to provide some partitioning of the flow on each side of the turret. The

fairing width must be adequate for internal suction ducting, but it must also be consistent with aft looking turret angle requirements. A width of 1/4 turret diameter would be a suitable compromise allowing a 4/1 axis ratio elliptic cross section (Fig. 20).

To accurately determine mass flow requirements for full-scale flight suction fairings would be difficult, if not impossible, without preliminary ground testing; however, an estimate might be based on the following requirement. The suction fairing should consume fluid at the rate at which fluid is entrained into the attached turret boundary layer.

The rate can be estimated using a very simplified assumption; namely, that the boundary layer growth is not affected by the turret curvature (i.e., flat plate boundary-layer correlations are applicable). Therefore, the mass entrained by a boundary layer at a distance of 1 diameter must be calculated, which is

$$\dot{M} = \rho u \delta^*$$

\dot{M} : mass flow per unit span

ρ : density

u : velocity

δ^* : displacement thickness

The density and velocity are taken as that of the freestream and the displacement thickness depends on distance from the leading edge and Reynolds number. For Reynolds numbers of order 10^7 , (i.e., turbulent boundary layers), the displacement thickness is about 1/600 of the distance (Ref. 19) which we will assume is of order the turret dia-

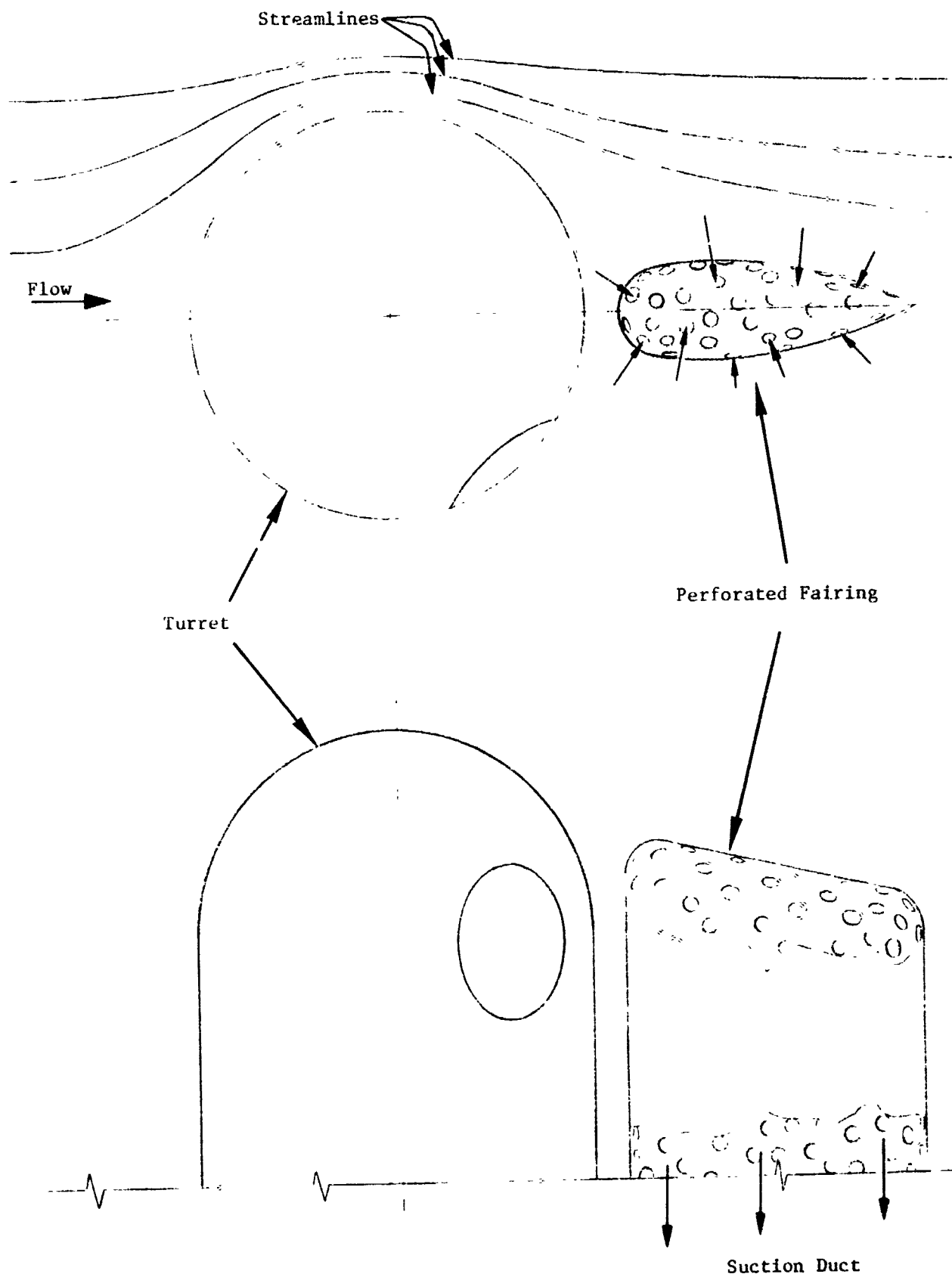


Figure 20. Suction Base Fairing

meter. Using sonic velocity, sea level density, and a span of 1 turret diameter, the suction fairing should consume mass at a rate of 1 kgm/s.

(2) Base Blowing - Base blowing should be applied through a very short fairing, placing the entraining jet in close proximity to the turret. The use of a short fairing may be justified since the jet will position the flow about each side of the turret (Fig. 21). An estimate of the mass flow requirements can be determined that the jet momentum must be a small fraction of the turret drag, possibly 1/100, (Ref. 20). The momentum flux from the jet is

$$S = \rho U^2 A;$$

where A; is the jet area.

Using freestream density and a jet area which is 10% of the turret area, the jet velocity must be about 3% of freestream to balance 1% of the turret drag (the turret drag coefficient is assumed to be 1). For sonic freestream velocity, sea level density and a 1 m-diameter turret, a jet velocity of 10 m/s would be estimated producing a 1 kgm/s mass flow.

(3) Base Jet Pumping - The jet fairing entrainment efficiency may be improved by adding a cowling (Fig. 10). The cowling/jet fairing would act as a jet pump drawing fluid from the turret base at a considerably improved rate. With proper design, the flow streamline would conform to the shape of the cowling without separation and would cause the pump efficiency to be excellent.

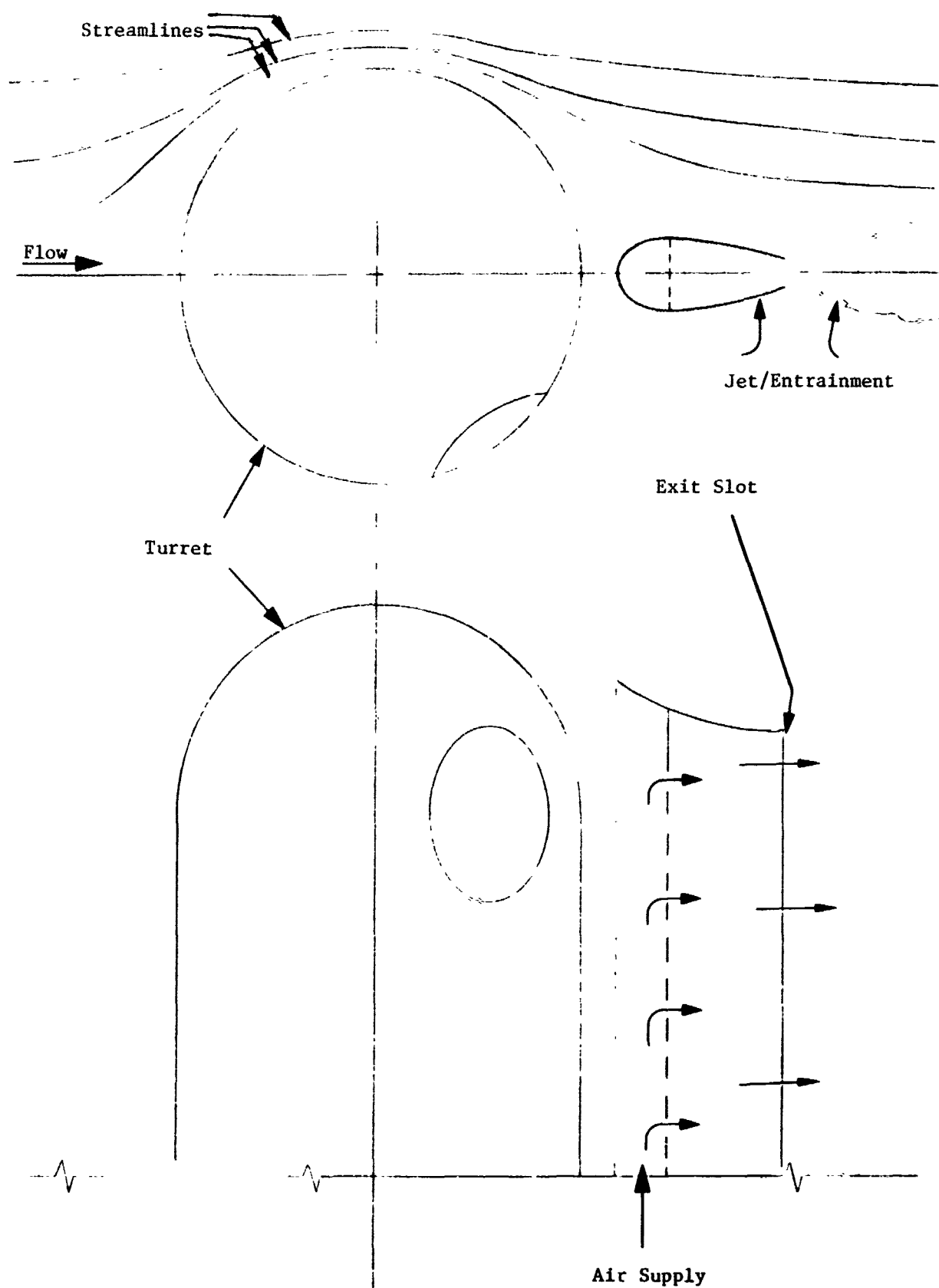
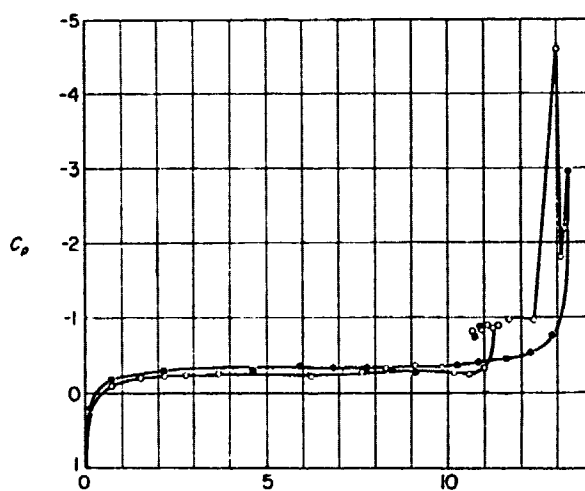


Figure 21. Blowing Base Fairing

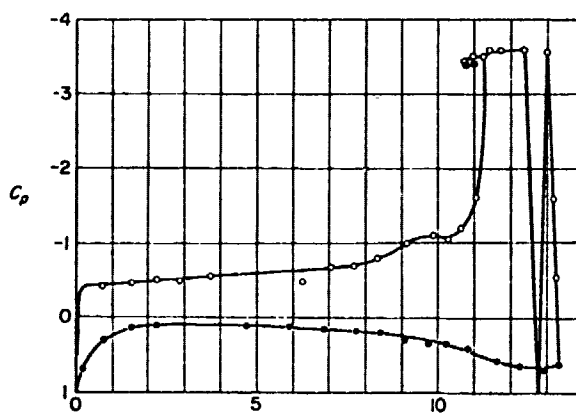
(4) Trapped Vortex/Suction - Control of the position, from which vorticity is shed by trapping such fluid in a cusped base fairing, is an attractive idea. This concept is based on work done at Princeton University (Ref. 21) where large flow deflection was attained over the trailing edge of a cusped wing. The suction vortex profile is shown in Figure 22. The zero angle-of-attack pressure distribution showed little effect until suction coefficient of 0.036 was reached when the vortex was apparently trapped and the lift coefficient jumped from 0.1 to 1.3. Craig* has proposed a modification of the trapped vortex concept for aircraft turrets in which the vortex is trapped in a cusped base fairing and, just as importantly, stabilized by stretching along the vortex axis through the application of suction at the base of the cusp (Fig. 23). Vorticity in the boundary layer is continually drawn off the turret, forming the trapped vortex from which air is continually moved at the base.

*Craig, J. E., "Flow Control and Screening Methods for Aircraft Turrets", presented at Control of Turbulent Separated Airflow about Aircraft Turrets Workshop at Air Force Weapons Laboratory, Kirtland Air Force Base, March 1980.

Suction-Vortex Profile



a. $C_Q = 0.0307$ $C_L = 0.096$



b. $C_Q = 0.0364$ $C_L = 1.275$

Figure 22. Zero Angle of Attack Pressure Distributions on a Suction-Vortex Profile

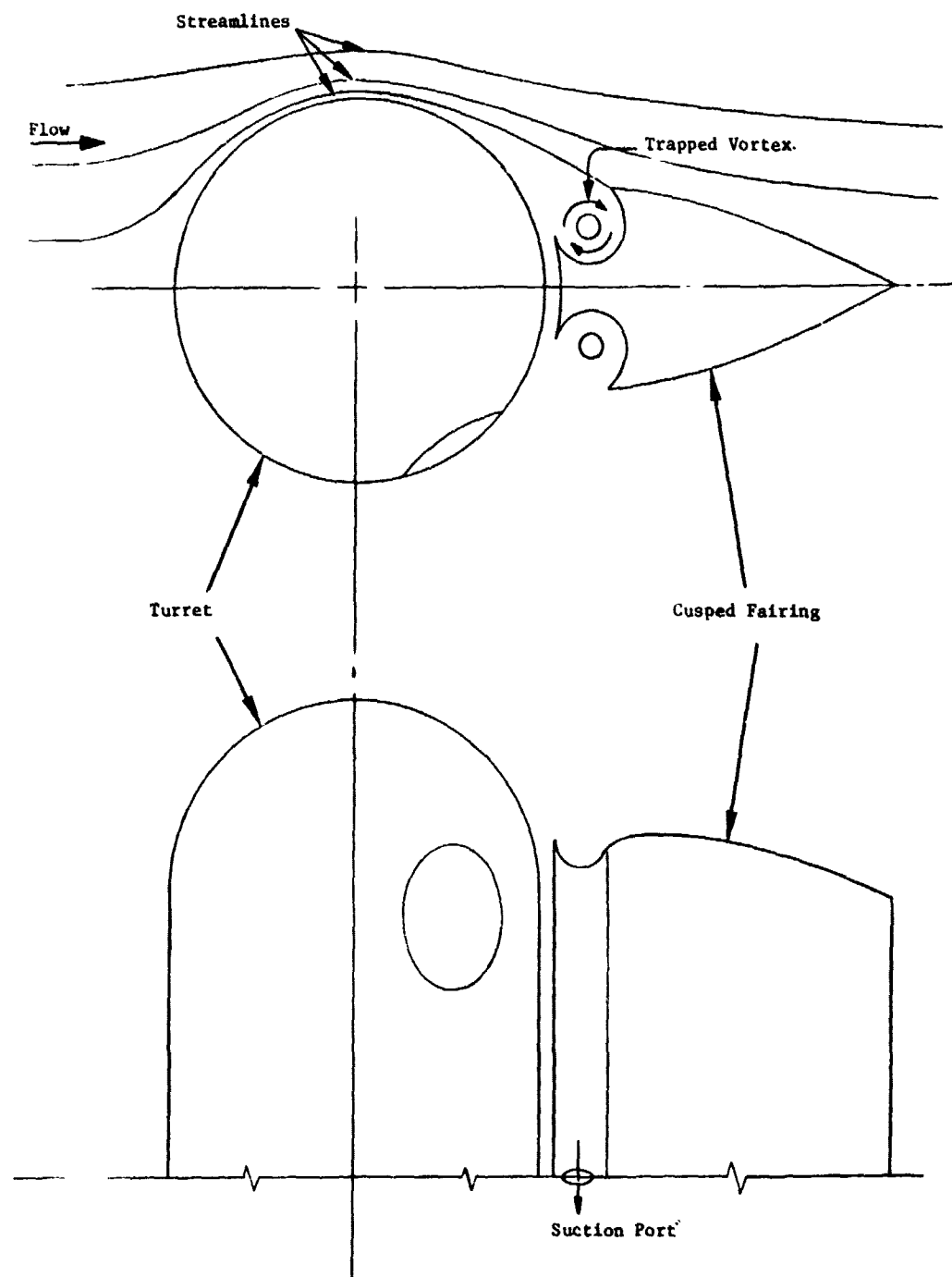


Figure 23. Trapped Vortex/Suction Fairing

III. SCREENING METHODOLOGY

Methods for screening conceptual flow-control techniques are fairly subjective; however, some rational screening methodologies are described in this section. Actually three types of screening methodologies are described:

- (1) basic airborne and weapon system compatibility
- (2) simplified flow-field calculations, and
- (3) flow-field simulation experiments

Basic airborne compatibility should be established in terms of blowing and suction power, flow-rate requirements, aerodynamic drag, and buffet levels. Weapon system compatibility must be considered because each control technique places different physical range limits on the turret angle.

Simplified flow-field calculations are probably the least developed of the methodologies. State-of-the-art flow calculations are modeling transonic flow over slender bodies with limited success (Horstman), as only gross-flow features, such as the pressure rise at shock separation, are determined with some reliability. Turbulence properties and shock location, two properties of significant importance to turret aerodynamics, are poorly modeled. Numerical simulation of transonic turret aerodynamics would (presumably) result in even poorer results because of the turret bluntness, although very little discussion of numerical analysis of blunt transonic flows is evident in the literature.

Flow-field simulation experiments are the best developed of the screening methodologies; in general, only partial simulation of the flow-field parameters is attained. The two most basic parameters simulated in experiments are Reynolds and Mach numbers. A parameter map depicts range of operation for a representative set of test facilities ranging from small, low-speed water channels to large, high-speed wind tunnels (Fig. 24).

The importance of simulating Reynolds and Mach numbers is a difficult question, but requires some discussion since no single facility can simulate both parameters. Mach number simulation is perhaps the more critical of the two parameters, since, in the transonic range, the flow configuration is strongly Mach number dependent. The drag coefficient of a sphere dependence on Mach number is shown in Figure 25. The rapid change in the transonic range is the net result of the Mach number dependence of many flow-field phenomena such as shock strength, shock boundary layer interaction, and separation. However, Reynolds number simulation can be just as important in many respects since its effect is primarily on boundary layer transition. For low Reynolds numbers, the boundary is laminar on the front of the cylinder resulting in a laminar shock, boundary layer interaction and perhaps even a laminar separation. For Reynolds numbers above about 2×10^5 , transition occurs on the forward surface of cylinders, the resulting turbulent-shock, boundary-layer interaction being of smaller spatial extent than the laminar one. This Reynolds number effect (the drag crisis) at subcritical Mach numbers is known to cause a sharp drop in

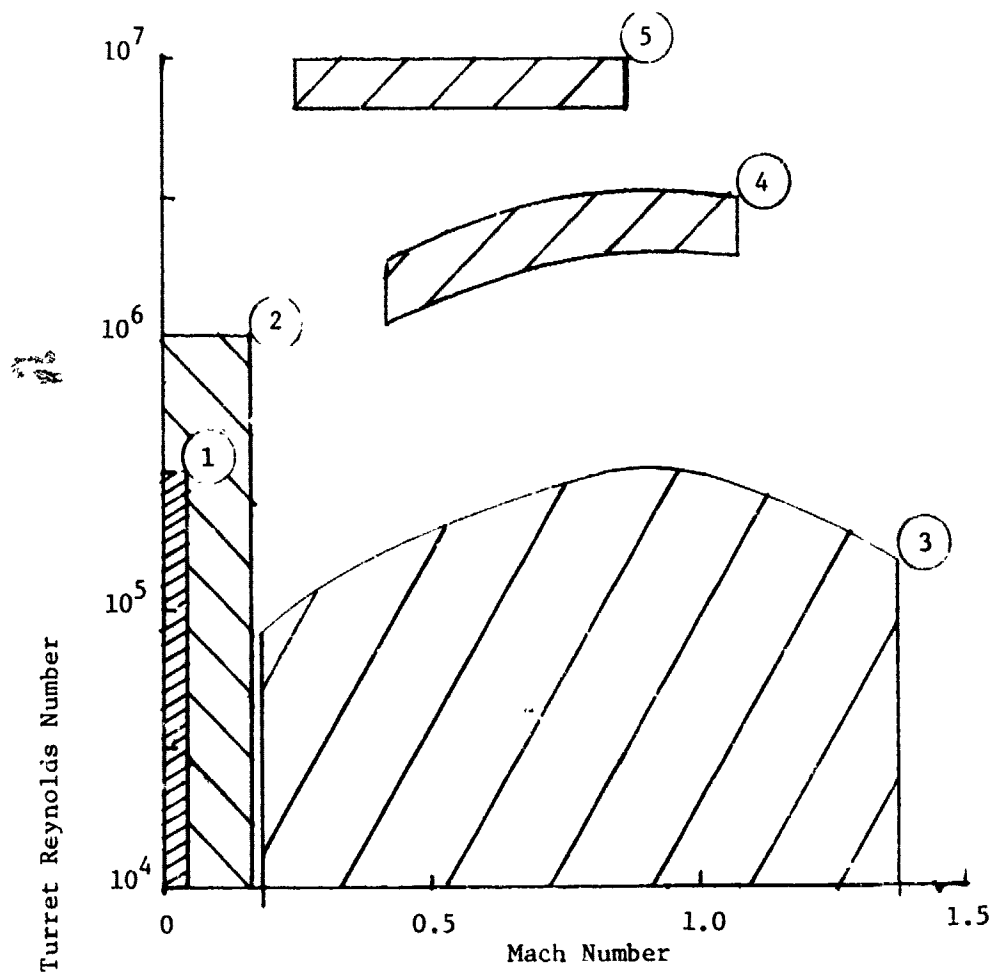


Figure 24. Reynolds/Mach Number Range of Selected Test Facilities

- (1) Cal Tech Free Surface Water Channel
- (2) Cal Tech 10-Foot Wind Tunnel
- (3) Ames 2 x 2 Foot Wind Tunnel
- (4) Ames 14-Foot Wind Tunnel
- (5) Flight (Airborne Laser Laboratory)

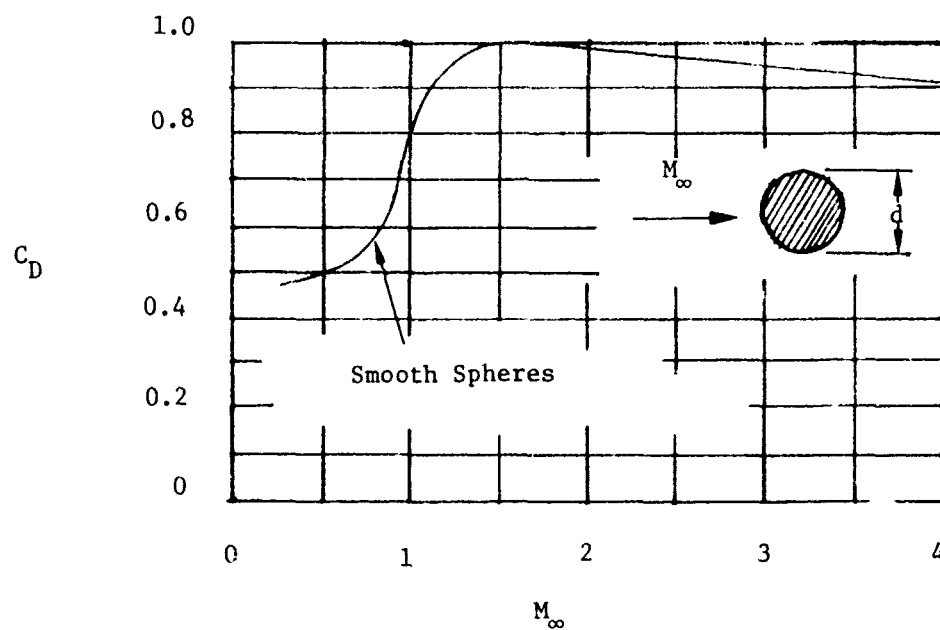


Figure 25. Sphere Drag Coefficient Dependence on Mach Number (Ref. 22)

cylinder drag coefficient as a result of the position of separation moving rearward for the case of the turbulent boundary layer. At compressible flow speeds, where the shock boundary-layer interaction occurs, the Reynolds number effect on this major flow-field adjustment is not well documented. Therefore, transonic testing in the 2×10^5 Reynolds number range should be avoided, if possible.

An alternative position might be to resort to boundary layer tripping to achieve some form of a turbulent shock interaction. It should be noted that extreme freestream turbulence levels are known to have a similar effect on transition as boundary layer tripping. Hence, these controversial issues must be carefully considered before alternatives are sought to natural transition.

1. SIMULATION

The following sections describe the fundamental methodologies for screening the flow-control concepts developed at the AFWL Flow Control Conceptual Design Study in aerodynamic or hydrodynamic test facilities. The screening of six fundamental flow-control concepts (Table 2) is described for characteristic test facilities which span the available Reynolds and Mach number simulation range (Fig. 24).

(1) Water Channels - Historically, water channels have been very useful facilities for initial exploratory testing of aerodynamic control devices (Ref. 23) because of their large Reynolds number capability, suitability for flow visualization, and ease and cost of model testing. The Cal Tech Free Surface (Ref. 24) has a

TABLE 2. GENERIC FLOW CONTROL CONCEPTS

ON-TURRET CONCEPTS

- 1) Surface Blowing
- 2) Surface Suction

OFF-TURRET CONCEPTS

- 3) Base Blowing
- 4) Base Suction
- 5) Base Jet Pump
- 6) Trapped Vortex Base Fairing

24- by 30-in. channel with a flow capacity of 25 ft/s. Reynolds number for a 3-in. diameter model is 5×10^5 which is well into the turbulent separation range for cylinders. The incompressible water channel facility at these Reynolds numbers will provide some simulation of the base flow region of the turret flow fairly well while the shock-boundary layer effects are absent from the cylinder body. Therefore, the water channel would be most useful for screening the base-fairing, flow-control concepts and considerably less useful for screening on turret concepts where the shock interaction must be simulated.

(2) Low Speed Wind Tunnels - Low-speed wind tunnels provide increased Reynolds number range over water channels primarily because of increased size. For example, the GALCIT 10-ft wind tunnel at Cal Tech has a flow capacity of 150 ft/s providing a Reynolds number greater than 10^6 for a 1 ft-diameter model. Boundary layer separation is well into the turbulent range allowing adequate screening of base-fairing flow-control concepts. The small advantage of increased Reynolds number over water channels is outweighed by the increased model and tunnel size, cost, and complexity of flow visualization. Hence, water channels are probably a better choice for initial incompressible screening tests.

(3) High-Speed Wind Tunnels - High-speed wind tunnels are available with test section dimensions from a few inches to many feet. Useful testing is limited to test sections larger than 2 ft. Small

transonic wind tunnels have already shown their usefulness (Ref. 23) in turret fairing development. With a flow capacity of near 10^3 ft/s and a 0.1-ft-diameter model turret, Reynolds number would be just into the turbulent separation range, 4×10^5 . Hence, turret models may or may not require boundary-layer tripping at critical Mach numbers to achieve turbulent separation. With or without tripping, the ability to simulate both compressibility and Reynolds number parameters in small scale transonic wind tunnels makes them attractive for screening tests.

Since the shock-boundary layer interaction will occur, these facilities can be particularly useful for screening on-turret control concepts. Turret area suction models will be easy to configure and test, but on-turret blowing is probably not possible in such small models. The model scale is too small for blowing base fairings, while suction base fairings could be configured to this scale.

(4) Large-Scale Wind Tunnel and Flight Testing - Large-scale, transonic wind tunnels are not amenable to screening of flow-control concepts, because of model and tunnel costs and testing complexity. Tunnels, such as the one measuring 14 ft. at NASA Ames, are better utilized for secondary efforts after fairly comprehensive, smaller scale testing. Reynolds numbers in these large scale tunnels reach close to flight values, thereby providing excellent data for prototype airborne turret-flow control devices.

2. SUMMARY OF SCREENING METHODOLOGY

A summary of the application of screening methodology to flow-control concepts is shown in Table 3. The value of screening each concept in various types of flows is rated from one to three -- one being desirable, two being adequate, and three being undesirable.

Water channels clearly have significant use in screening the off-turret concepts, and perhaps small-scale, transonic wind tunnels can be used to screen on-turret concepts.

TABLE 3. SCREENING METHODOLOGY APPLICATIONS

	Incompressible ($M < 0.4$)		Compressible ($M > 0.4$)	
	Laminar ($Re < 2 \times 10^5$)	Turbulent ($Re > 2 \times 10^5$)	Laminar ($Re < 2 \times 10^5$)	Turbulent ($Re > 2 \times 10^5$)
On Turret Concepts				
Surface Blowing	3	2	2	1
Surface Suction	3	2	2	1
Off Turret Concepts				
Base Blowing	3	1	2	1
Base Suction	3	1	2	1
Base Jet Pump	3	1	2	1
Trapped Vortex Base Fairing	3	1	2	1

Rating System

- 1) desirable
- 2) adequate
- 3) undesirable

IV. SUMMARY AND RECOMMENDATIONS

- High-lift airfoil flow-control technology can be applied conceptually to flow control of airborne laser turrets.
- Six examples of flow-control concepts, and their mechanism of control, have been described.
- Screening methodologies, using a selection of testing facilities, have been applied to flow-control concepts, and, as a result, water channel and perhaps small-scale, transonic wind tunnel screening tests are recommended.

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